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A Method to Assess and Compare Proving Grounds in the Context of Automated Driving Systems*

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Abstract— **Automotive proving grounds currently face an increasing complexity in testing requirements, especially in the field of automated driving. Thus, the variety of necessary test infrastructure grows. This challenges proving ground operators to constantly satisfy the demand. Requirements are a quick adoption of existing test tracks including its facilities and enhancements of the test infrastructure portfolio. Commercial proving ground operators usually strive to provide a broad set of test tracks so their customers can conduct most tests at one location. Customer loyalty is a key success factor for proving ground operators. A sufficient variety of test tracks and test infrastructure is a lever for customer loyalty. This paper provides a method to measure the quotient of testing demand satisfaction for automated vehicles. This allows benchmarking with other proving grounds. Furthermore, this method can be used to identify gaps between the current portfolio and the demand. Afterwards, action plans can be generated in order to close these gaps.**

I. Introduction

With an increasing number of driver assistance systems and a stronger engagement to reach market-ready automated vehicles, the testing requirements grow. Reasons are functional necessities due to a higher number of sensors, new rating procedures and new standards. Hence, commercial and manufacturer-internal proving grounds must strive to quickly adopt and enable new tests.

This paper depicts a valid concept for automotive proving grounds to measure its versatility in order to infer actions for improvement. The concept allows a structured investigation of the gap between proving ground requirements and the current setup. Applications for this concept are benchmarking with competing proving grounds and other manufacturers, continuous improvement and agile realization of new testing standards.

The research for this paper is part of a research project regarding development of effective test infrastructure for automated systems. In order to validate this method it has been applied to the Mercedes-Benz proving ground in Immendingen, Germany. It provides more than 30 different test modules and is therefore a proving ground with an expectable high versatility. It was therefore chosen to allow a thorough validation of the method.

The research for this paper in the fields of engineering and economy was conducted from September 2019 through February 2020. Its design included the steps of data collection regarding current international testing specifications (certifications, ratings, standards and functional testing approaches), concept design, validation and emendation.

The following chapters describe related work, the conceptual design and its foundation, the application process and discuss challenges and opportunities for further research regarding the versatility measurement for proving grounds.

II. Related Work

A literature research was conducted in order to identify methods to assess the performance and especially the infrastructure portfolio of proving grounds. Although approaches to design proving grounds could be found, no method to assess proving grounds was identified. The following literature supported the development of this assessment method.

The Society of Automotive Engineers (SAE) defined five levels of automation for driving systems and further terms within this context. These levels and terms are an accepted standard within the automotive industry. This paper uses the definitions of SAE J3016 [1].

The PEGASUS project had the goal to develop standardized procedures to test automated vehicles. In this context, the six-layers-model was designed. According to documentation, the model can be used to easily define functional testing scenarios [2]. The model can also be used for classification of proving ground components and is therefore relevant for this paper.

In 2014 Nowakowski, Shladover, Chan and Tan addressed in their paper “Development of California Regulations to Govern the Testing and Operation of Automated Driving Systems” issues for testing of automated vehicles. Especially their proposal for minimum behavioral competencies of automated vehicles [3] results in further requirements for proving grounds. These competencies were reviewed by 76 experts [4] and reworked accordingly. The U.S. National Highway Traffic Safety Administration (NHTSA) promotes these competencies as well [5].

Waymo, a self-driving technology development company and associate company of Google, has published a safety report for automated vehicles. The safety report builds up on

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the behavioral competencies and extends them with further competencies [6]. These can support the development of requirements for proving grounds for all levels of automated driving as well.

III. Method

A. General Overview

The more tests a proving ground enables, the more versatile it is. The versatility index is a Key Performance Indicator (KPI) for automotive proving grounds. It displays the current degree of demand satisfaction for test engineers. Furthermore, it quantifies the service portfolio. The versatility of a proving ground V_p can be described as the quotient between the quantity of executable tests on a proving ground T_e and the quantity of necessary tests to validate specific functions T_n, in this case automated driving functions.

$$V_p = T_e / T_n \tag{1}$$

It is obligatory to determine the necessary tests before the executable tests. In this formula, a test is defined as a precise description of equipment, procedures and orders to simulate driving situations and measure the systems' reactions. Tests without proving ground requirements and repetitions are not considered. The versatility theoretically can be determined for all driving functions. However, automated driving functions are used as an example in this paper, because the necessary tests are more novel compared to classic driving dynamics, comfort and endurance tests, for example. The benefit of this method is the possibility to identify gaps. Therefore, the versatility needs to be measured on different levels, which all together compose an all-embracing KPI. Fig. 1 shows an overview of the versatility index system with its performance measures for automated driving systems.

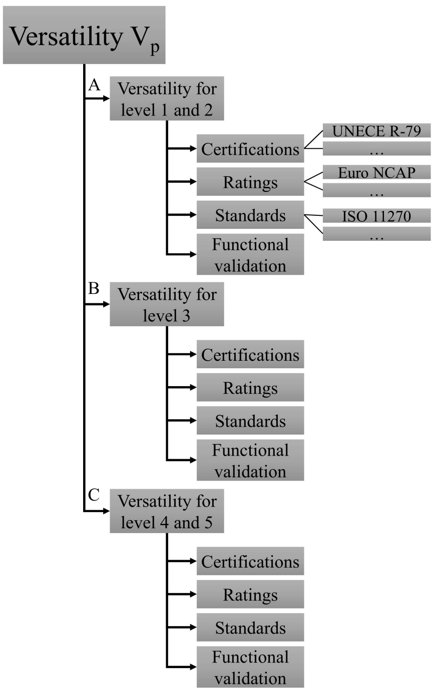

Figure 1. Versatility Index System for Automated Vehicles

The utilization of the versatility formula results in the gain of a value between 0 and 1. If the result is 0, the proving ground does not provide any opportunity to test automated vehicles. A value of 1 would mean that the proving ground enables every test for automated vehicles.

In the case of automated driving functions, the versatility can be structured in three categories: a) SAE level 1 and 2, b) SAE level 3 and c) SAE level 4 and 5. The reasons for this structure are the different responsibilities for the dynamic driving task. In level 1 and 2, the human operator is responsible for environmental monitoring and lateral or longitudinal acceleration. In level 3, the driver acts as a fallback. Therefore, responsibilities may differ. In level 4 and 5, the system is responsible for the environmental monitoring and the dynamic driving task. The specific necessary tests are described in certifications (e.g. UNECE R-79), rating protocols (e.g. Euro NCAP), standards (e.g. ISO 11270) and further test protocols for functional validation as part of the development process. These protocols for functional validation are technology- or manufacturer-specific. Different approaches can be used to design tests [7]. Certifications and standards for automated driving are mainly valid on an international level. Rating procedures may vary between countries. Rating protocols for the United States, which are published by the NHTSA [8, 9, 10, 11] and the Insurance Institute for Highway Safety (IIHS) [12, 13], for instance, describe 34 (26+8) tests, while the program for China (C-NCAP) consist of 39 tests [14]. At least for the ratings, it is recommended to apply a weighting coefficient. If manufacturer-internal proving grounds are assessed using the versatility index, the particular market share for those countries could be used. As an example, in 2018 Mercedes-Benz sold app. 1,261,000 cars/vans in Europe, 443,500 cars/vans in North America, 706,800 cars/vans in China and 393,000 cars/vans in other markets. In total, Mercedes-Benz sold 2,804,200 cars/vans globally [15]. Hence, the largest market for Mercedes-Benz is Europe (≈ 45 %), the second largest is China (≈ 25 %) and the third largest is North America (≈ 16 %). These coefficients can be used, at least for ratings, to obtain a more precise versatility. However, for the Mercedes-Benz proving ground in Immendingen the versatility for ratings was not significantly (< 3 %) different using these weighting coefficients, because the European New Car Assessment Program (Euro NCAP) provides significantly more tests than other organizations.

B. Versatility for Level 1 and 2 (Category A)

Category A comprises level 1 and 2 and includes certifications, ratings, standards and functional validation.

Certifications are statutory provisions and therefore legally binding. Hence, they can be considered the most important, since their requirements need to be met in order to receive road homologation. The United Nations Economic Commission for Europe (UNECE) enacted five regulations that particularly affect automated driving systems: regulation no. 13H (braking systems), no. 79 (steering systems), no. 130 (lane departure warning systems), no. 131 (advanced emergency braking systems) and no. 139 (brake assist systems). The connection to the automated driving systems is established trough the dynamic driving task. The dynamic driving task consists of operative and tactical functions. Pure operative functions are longitudinal and lateral control. The monitoring of the environment and response execution are both operational as well as tactical tasks. The regulations 13H and 79 describe requirements for longitudinal control (acceleration and braking) and lateral control (steering). The other regulations focus on the monitoring of the environment and the object and event response execution.

Ratings like New Car Assessment Programs (NCAP) aim at evaluating cars that are introduced to the market regarding their passive and active safety. The results are published to inform potential customers. Good results can convince a customer to buy a car, while insufficient results may constrain sales. Hence, car manufacturers are usually keen to achieve positive results. Current and soon oncoming rating protocols can be separated in two main functions: Autonomous Emergency Braking (AEB) [16, 17] and Lane Support Systems (LSS) [18]. Current AEB test protocols demand three kinds of targets. These are vehicle targets, driving Vulnerable Road User (VRU) targets like cyclists, scooters and motorbikes and pedestrian targets. Tests within rating protocols are usually described very precisely and can be numbered. The number of tests can simply be compared to the number of tests that are executable on a proving ground. However, rating organizations may use their own weighting coefficients to calculate the results. Relevant rating programs and organizations are for example ASEAN NCAP, China NCAP, Euro NCAP, IIHS, i-VISTA, Japan NCAP, Korean NCAP, Latin NCAP and US NCAP. Generally, the Euro NCAP can be considered as a very extensive rating program. Other rating organizations commonly build up on their tests.

There are several **standards** existing for driver assistance systems. Table I. lists relevant standards.

TABLE I. STANDARDS FOR DRIVER ASSISTANCE SYSTEMS

Number	Scope of Application
ISO 11067	curve speed warning systems
ISO 11270	lane keeping assistance systems
ISO 15622	adaptive cruise control systems
ISO 15623	forward vehicle collision warning systems
ISO 16787	assisted parking systems
ISO 17361	lane departure warning systems
ISO 17386	maneuvering aids for low speed operation
ISO 17387	lane change decision aid systems
ISO 19237	pedestrian detection and collision mitigation systems
ISO 22178	low speed following systems
ISO 22839	forward vehicle collision mitigation systems
ISO 26684	cooperative intersection signal information and violation warning systems

Vehicle manufacturers are not legally required to comply with those standards. However, these standards aim to reflect the state of the art competencies of driver assistance systems. Furthermore, these standards address manufacturers worldwide. Similar to the rating protocols, most standards provide precisely described tests including specific requirements for proving grounds.

Disregarding official test protocols, **functional validation** is always required to ensure the vehicles' functionality. Hence, every car manufacturer needs to have internal validation test cases depending on their automated driving systems' functions. The tests for functional validation can be designed using the proposal from Nowakowski et al. [3], which was extended by Waymo [6], regarding the competencies an automated driving system should have. These competencies include a broad range of situations the system may be confronted with while operating on public roads. These challenging situations are for instance a policeman or policewoman regulating the traffic, navigation in parking lots as well as encounters with school busses, especially in the USA. The automated vehicle must respond to these situations by either performing a driving maneuver or handing over to the human user (level 3 vehicles). However, the system has to interpret the situation correctly and act upon its limitations. Requirements for proving grounds can be derived from these behavioral competencies as well.

C. *Similar formula*

Because there currently are no certifications, no rating protocols and no standards valid or harmonized for level 3, 4 and 5 systems, other reference points must be utilized to measure the versatility for the categories B and C. Automotive manufactures are using internal tests for the functional validation of level 3, 4 and 5 systems. Fig. 2 shows an interim system for the versatility index. Category A is identical in Fig. 1 but is listed again for the sake of completeness.

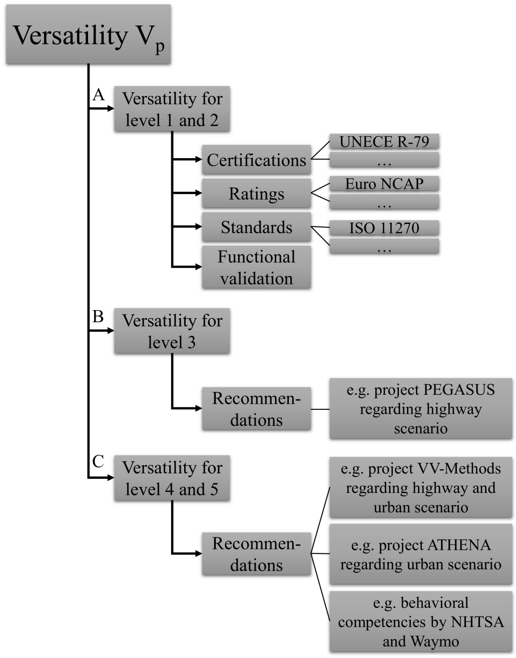

Figure 2. Interim Versatitlity Index System for Automated Vehicles

To identify the versatility of a proving ground for level 3, 4 and 5, two approaches can be used. It is possible to utilize internal tests or design tests based on the mentioned behavioral competencies. Another way is to identify the versatility based on proving ground infrastructure requirements instead of tests. The results, however, could be less meaningful, since the feasibility of tests at a given proving ground is more important than the number of proving ground infrastructure requirements that are fulfilled. For example, one fulfilled proving ground infrastructure requirement (e.g. a flat dry surface with 10 hectares) could enable 20 tests while another fulfilled requirement just enables 2 tests. However, those two tests could be more important than the other 20. Therefore, both approaches are valid. Thus, the second option based on proving ground infrastructure requirements is used for two reasons: to explain how the approach works and because this method can be conducted independently from manufacturer-internal tests. For this purpose, public recommendations from federal organizations like NHTSA, private companies like Waymo and results from various projects were used. Further internal specifications may also be considered (e.g. from project ATHENA for Mercedes-Benz).

To calculate the versatility based on proving ground infrastructure requirements instead of tests, a different formula can be used. The quantity of fulfilled requirements R_f is simply divided by the total quantity of requirements R_n. The result V_c is the coverage ratio for proving ground infrastructure requirements.

$$V_c = R_f / R_n \tag{2}$$

It is expected that tests will increasingly be conducted using virtual simulation to save development time and costs. Nevertheless, corner scenarios and critical situations probably will still be tested physically as a verification method within the near future.

As mentioned in chapter II, the six-layers-model, which the PEGASUS project designed, can be used to classify proving ground infrastructure requirements. Its original purpose is to assist the design of test scenarios. The six layers are [2]:

1. Road (e.g. geometry, physical description)
2. Infrastructure (e.g. traffic signs, guard railing)
3. Temporary influences (e.g. road construction)
4. Movable objects (e.g. vehicles, pedestrians)
5. Environment conditions (e.g. light, weather)
6. Digital information (e.g. LTE)

The utilization of these six layers supports a structured examination of fulfilled requirements. Highly automated driving (level 4) does not necessarily require a driver anymore as long as the system operates within the domain for which it was designed. Therefore, depending on the planned Operational Design Domain (ODD), the proving ground infrastructure can differ. A fully automated driving system is capable of operating without ODD limitations. Under the assumption that the proving grounds' purpose is to simulate the system specific ODD, the requirements for fully automated driving systems (level 5) have to be higher than those for level 1, 2, 3 and 4.

D. *Versatility for Level 3 (Category B)*

Tests for conditional automated driving systems (level 3) are summarized in category B. In level 3, the system performs the dynamic driving task by itself and hands over to the human user when it reaches its limitations. Handover test scenarios therefore mainly occur for level 3 systems and have particular demands. Hence, they establish their own group of test scenarios. A possible use case for level 3 is the application on highways, since the ODD is not as versatile as in urban environments. The PEGASUS project describes this application under the name “highway chauffeur”. Requirements can be derived using formula 2.

E. *Versatility for Level 4 and 5 (Category C)*

The system at this stage is capable of performing all driving functions under certain (level 4) or all (level 5) conditions. However, in both levels there is no driver necessary as long as the level 4 vehicle operates in its ODD. The project “VV-Methoden” (German for VV-Methods) is the follow-up of the PEGASUS project. While the PEGASUS project focused on highway scenarios and level 3, the follow-up is supposed to provide methods to validate and verify level 4 and 5 systems in urban environments [13]. Another project is ATHENA, a joint project of Mercedes-Benz and Bosch, which aims at developing level 4 and 5 systems for urban environments [20] and in which, for development purposes, test protocols were designed. The extended set of behavioral competencies [3, 6] can also be used, since it recommends system capabilities automated driving systems at level 4 and 5 should or must have. Requirements for proving grounds can be derived from these.

F. *Procedure for Application*

The following Fig. 3 highlights the necessary steps to determine and increase the versatility of a proving ground.

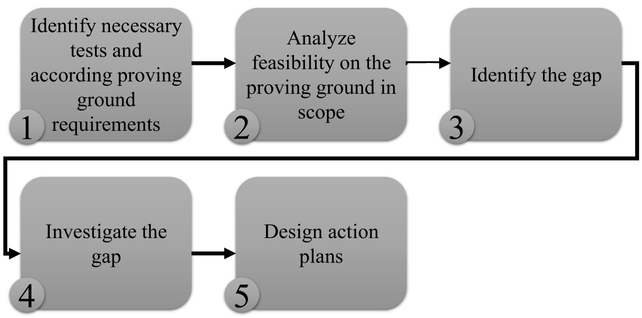

Figure 3. Versatlity Application Procedure for Proving Grounds

First, it is obligatory to identify necessary tests to validate automated driving functions and the according proving ground requirements. Therefore, certifications, ratings, standards and functional validation protocols need to be studied. Furthermore, additional recommendations and current projects can be used to mitigate missing specifications. In step two, the feasibility of these tests according to their requirements needs to be investigated for the proving ground in scope. The minimum requirements for each test are often directly described within the test setup. Missing parameters can be calculated. The required length of a test track, for instance, can be determined by the acceleration of the test vehicle and targets, the speed the test has to be conducted with, the maneuver duration and the braking deceleration. To declare a test as executable with this method, all test infrastructure specifications must comply with the requirements accurately. The requirements for proving grounds can be classified using the six-layers-model from the PEGASUS project. If the quantified results of step one and two are compared, it is possible to determine the versatility and identify the gap. The gap includes all tests that are not executable on the proving ground in scope. In step four, this gap is investigated further to extract the causes for non-executable tests. Those non-executable tests are expectably caused by not existing proving ground parameters, for instance missing pedestrian targets. Finally, in step five, action plans are designed to close the gap and enable specific sets of tests. Therefore, the actions are rated according their implementation efforts (time and costs) and their impact on the versatility index. Actions with low time and cost efforts but high impacts on the versatility should be executed ad hoc. Furthermore, it is recommended to conduct a chance-risk-analysis. If implementation efforts involve construction work, an organizational solution can be taken into consideration.

IV. Method Validation

To validate the methods functionality it has been applied to the new Mercedes-Benz proving ground in Immendingen, Germany. Since Mercedes-Benz supported this research, the necessary information was made available. In order to apply the method, the following parameters need to be known.

- Geometry of test tracks, especially length, width, curve radiuses, friction coefficients, cross-fall, longitudinal gradient, surface materials, the maximum driving speed and construction specifications (bridges, gantries, tunnels, etc.) including their clearance
- Road surface marking measurements and colors, guard railing positions, types and number of traffic signs and curbstones
- Types of facilities and stationary machines (e.g. irrigation systems, gantries, target movers and technologies to simulate adverse weather conditions)
- Possibilities of testing under night conditions
- Types of available test equipment such as targets (e.g. pedestrians, cyclists, pillars for parking maneuvers), platforms and dummies but also traffic lights, safety barriers and cones
- Types of communication platforms like GSM, UMTS and LTE but also the availability of signal correction stations (e.g. for differential GPS)

Some of this information may be requested at the building authorities or other public offices. According to the German Federal Immission Control Act § 4 appendix 1, plans for permanent race and test tracks require a public review process [21]. Regulations may be different in other countries.

Table II. shows exemplary results for category A. To achieve a detailed benchmarking, these performance measures can be compared with those for other proving grounds on each level.

TABLE II. Example Versatility of Immendingen Site

Versatility Index Layer (without weighting)	**Versatility**
A: Level 1 and 2	424/518 ≈ **0.82**
Certifications	7/10 = 0.70
UNECE R-79 – steering equipment [22]	4/7 ≈ 0.57
UNECE R-131 – advanced emergency braking systems [23]	3/3 = 1.00
Ratings	406/481 ≈ 0.84
Euro NCAP	368/442 ≈ 0.83
China NCAP	38/39 ≈ 0.97
Standards	11/27 ≈ 0.41
ISO 17361 – lane departure warning systems [24]	9/25 = 0.36
ISO 19237 – pedestrian detection and collision mitigation systems [25]	2/2 = 1.00

Concerning the requirements for steering equipment tests from UNECE R-79, the Mercedes-Benz proving ground has straightaways with lane markings according to UNECE R-130. However, it lacks some required radiuses. In regards to Euro NCAP, a road edge simulation and single lane markings are missing. All required targets for the ratings are available. For ISO 17361 straightaways with lane markings and curves with different radiuses are required. Not all radiuses are available in Immendingen. ISO 19237 demands e.g. specific targets, roads with 1 % slopes and streetlights. The targets, 1 % slopes and non-stationary streetlights are available. In general, most tests that cannot be executed in Immendingen are based on specific lane markings. Hence, it can be inferred that these gaps may for instance be eliminated through flexible lane marking concepts on a flat asphalt surface.

As explained earlier during the conceptual phase of the research for this paper, it was considered to measure the quotient between proving ground infrastructure requirements instead of tests. This approach is theoretically also possible but may not be that meaningful. The reason is that there are multiple ways to fulfill a proving ground infrastructure requirement. A flat 10 hectares asphalt surface allows driving at different speeds in different radiuses. Several asphalt roads may serve the same purpose. Tests are rather constant and establish the bridge between proving ground operator and customer.

As part of the research, an Excel sheet has been designed that allows checking off the specific proving ground requirements as of December 2019. It automatically calculates the possible tests and the versatility for each category and layer. It furthermore summarizes the gap to support the user designing appropriate action plans. Fig. 4 in the appendix highlights the user interface for this tool.

In summary, the application of the method shows that it is possible to determine the versatility for each level and calculate the all-embracing KPI. Furthermore, the Excel sheet could be used to identify which test infrastructure enhancements have the biggest impact on the proving ground's versatility. These infrastructure enhancements should be implemented with a high priority. Hence, it can be concluded that the proposed method provides a valid mechanism to improve the proving ground performance through demand-based portfolio extensions.

V. Conclusion

The versatility index describes the ratio of executable tests for automated driving systems on a proving ground compared to the necessary tests. These tests are described within certifications, ratings, standards and functional validation protocols. Since these sources may have different importance, it could be beneficial to weight them differently. Tests may also be weighted with regard to customers and markets. Further experience in the application of this method is required to define effective weighting factors. The method could therefore be applied to manufacturer independent proving grounds, such as UTAC CERAM in France, Applus IDIADA in Spain or Automotive Testing Papenburg in Germany. In addition, proving grounds with a focus on automated vehicles, like Zala Zone in Hungary, Mcity in the USA or Transpolis in France, could be assessed, too. However, some proving grounds may explicitly aim for a niche and will therefore have a low versatility but positive financial results. Hence, each proving ground may weight tests and sources differently. In any case, proving ground operators strive to satisfy the customers' demands and are therefore generally keen to provide a high versatility. The described method allows proving ground operators to determine and improve their versatility. Therefore, the lack of proving ground infrastructure needs to be analyzed. Then, action plans can be designed to eliminate these gaps. Finally, customers may also use this method to decide which proving ground is a good strategic partner for future endeavors.

Appendix

Proving Ground Gap Analysis

Layer 4 - Moving objects: vehicles, pedestrians, etc.

#	Requirement	Source	Fulfilled by the proving ground in scope?	
			yes	no
1	Static target of category M1 AA saloon (regular high volume series production) or a soft target representative of such a vehicle (identification characteristics shall be aligned with the technical service)	UNECE R-131	X	
2	Moveable target of category M1 AA saloon (regular high volume series production) or a soft target representative of such a vehicle (identification characteristics shall be aligned with the technical service) with a max. speed of 67 km/h	UNECE R-131	X	
3	Test target with the physical size, shape, surface profile and a reflection coefficient of test target RCTT of a representative motorcycle	ISO 15623	X	
4	Motorcycle target wit a length of 2.0 m to 2.5 m, a width of 0.7 m to 0.9 m (without side mirrors) and a height of 1.1 m to 1.5 m (without windscreen)	ISO 17387		X
5	Pedestrian test target (referring to ISO 19206-2)	ISO 19237	X	
6	Euro NCAP Pedestrian Target adult (EPTa)	Euro NCAP	X	
7	Euro NCAP Pedestrian Target child (EPTc)	Euro NCAP	X	
8	Global Vehicle Target (GVT)	Euro NCAP	X	

Figure 4. User Interface of Proving Ground Assessment Tool

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